Mesoscale Ionospheric Prediction

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LONG-TERM GOALS

The long-term goals of this project are to first develop a three-dimensional time-evolving non-linear numerical model of the mesoscale ionosphere, second to couple the mesoscale model to a mesoscale data assimilative analysis, third to use the new data-assimilative mesoscale model to investigate ionospheric structure and plasma instabilities, and fourth to apply the data-assimilative mesoscale model to applications of interest to DoD.

The complete system, consisting of the mesoscale non-linear model, the mesoscale data assimilation analysis, and the coupling between the model and analysis, is a Mesoscale Assimilative Prediction System (MAPS) that can be used for both scientific and DoD applications.

OBJECTIVES

The first scientific objective of this research project is to derive a full four-dimensional (three spatial dimensions and one temporal dimension) Fourier modal analysis of the basic ionospheric fluid equations, keeping all non-linear terms. The derivation must be valid over spatial scales from meters to 100s of kilometers and temporal scales from seconds to 10s of minutes. The fluid equations include the ion density continuity equation, the electron and ion velocity equations, and the divergence of the current.

The second objective it to solve the non-linear equations derived above through a numerical iterative approach in frequency-wavevector space. Once the iteration is complete the wave modes are Fourier transformed back into the spatial-temporal domain.

The third objective of this research project is to couple the model, while in the frequency – wavevector domain, to observations of the ionosphere through a data assimilative technique.

APPROACH

The approach followed during the course of this research project is as follows:

Mesoscale Model

1. It is assumed that over some 3D regional volume and period of time that the large-scale ionosphere can be considered constant. The ionospheric equations are then perturbed about this background state.

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2. Fourier transforms of the perturbed equations are made in space and time. Non-linear products in real space-time become convolutions in the Fourier domain.

3. The Fourier transform in time is actually a Laplace transform. This allows incorporating the initial conditions of the perturbations into the non-linear analysis. This implies the back-transform is over a complex frequency. In fact, it is over a constant imaginary value, larger than the largest imaginary frequency from any poles that exist in the system, and parallel to the real axis.

4. Variables that are not self-consistently solved for such as neutral wind perturbations are considered to be inputs to the system.

5. A linear analysis of the system is performed, poles in the determinant of the resulting matrix are found, and the largest imaginary part of the frequency of all poles is determined. Then when the model amplitudes are determined, they are determined for the complex frequency.

6. The non-linear iteration is performed. Only modes greater than some small epsilon are tracked, which greatly speeds up the process. When the modal amplitude change from one iteration to the next is sufficiently small, the code exits.

7. Finally, a back Fourier transform over space and time is performed, using the imaginary component of frequency found in step 5.

Mesoscale Data Assimilation

1. Start with the global data assimilation algorithm Ionospheric Data Assimilation Three Dimensional (IDA3D), which was developed under ONR grant N00014-97-0236.

2. Instead of solving for 3D voxels of electron density, alter IDA3D to solve for the complex coefficients of a basis set of 3D plane waves.

3. Restrict the basis set to a regional volume and time period, which effectively sets the number of modes.

4. Obtain perturbed / irregular data over the region of interest. Such data can be obtained from GPS scintillation receivers for example. Or, if perturbed data is not available directly, do the following: Run the Global IDA3D to obtain a background solution and then use the background to subtract off the large scale background values from the data. This gives perturbed data over the spatial-temporal region of interest

5. Ingest the perturbed data into the Plane Wave version of IDA3D and compute perturbed solutions

Couple the Mesoscale Model to the Mesoscale Data Assimilation to Produce a Mesoscale Assimilative Prediction System (MAPS)

1. Data-driven inputs to the model consist of observations of mesoscale structure, as well as observations (or model estimates) of the large-scale fields.

2. Typically the mesoscale observations are perturbations in electron density, and are used at the initial time as the initial conditions of the mesoscale model.

3. Occasionally observations are available continuously, and can be used to directly constrain the model. For these cases, at each iteration, the perturbed densities are constrained to match the observations. This in turn effects the overall estimation of the other state variable – the electric potential, and electron and ion velocities.

The key individuals in completion of the technical tasks described above are Dr. Bust, the PI, Scott Kilpatrick, an undergraduate major in computer science, and Natalie Curtis, a graduate student in physics. Dr. Bust is responsible for the overall derivation, development, implementation and testing of MAPS. Mr. Kilpatrick is responsible for the numerical coding of the algorithm. Ms. Curtis is responsible for the conversion of IDA3D to a plane wave mesoscale assimilation program.

WORK COMPLETED

With ~ 1/3 of a year of resources left, all the work in the mesoscale prediction model has been completed. The mesoscale data assimilation is currently being tested. It is anticipated that with the remaining resources the mesoscale data assimilation task will be complete and tested, and that sample regional perturbed data from the Japan Geonet system will be used as a test bed for coupling the mesoscale data assimilation model to the mesoscale prediction model.

RESULTS

A test case was run with the new non-linear modal model. The case chosen was based upon the linear two-stream instability analysis found in Kelley [1989].

Background input values

- Electron and ion temperatures of 300 degrees Kelvin
- O_2^+ ion species
- Electron-neutral collision frequency = 6.0E4 Hz
- Ion-neutral collision frequency = 3.0E3 Hz
- East background electron velocity = 4.0 km/s
- Ion velocity zero, other electron velocity components zero.

Initial modes (eastern neutral wind perturbations of 50 m/s) – only angular frequency (radians/sec), and eastern (y) spatial wavenumber (km-1): (0.17,0.1), (0.17,.01), (.18,0.1), (.18,0.01), (.19,0.1), (.19,0.01), (.20,0.1), (.20,0.01)

Angular frequency modes go from .01 1.0 in .01 steps

Spatial frequency goes from -1.0, 1.0 km-1 with .01 steps

The following four figures present plots of the percent density variation. The intensity of amplitude of the Fourier modes is plotted as a sequence of non-linear iterations. The x-axis is frequency in Hz and the y-axis is eastern spatial wavenumber in inverse kilometers. The first plot represents the initial set of modes that were input (described above). The second plot is three iterations into the process and

several new modes have developed at different frequencies and wavenumbers. The third plot, 6 iterations into the process, shows the continuing development of new modes. The final plot, 9 iterations into the process, shows minor changes from the results at 6 iterations, and demonstrates that the non-linear iterative procedure is converging nicely. It is interesting to note that this is a fairly simple case – it is only 2 dimensional, and only 8 initial modes were excited. However, even for such a simple case the nonlinear procedure shows a number of additional modes – of equal amplitude to the initial modes – being created.

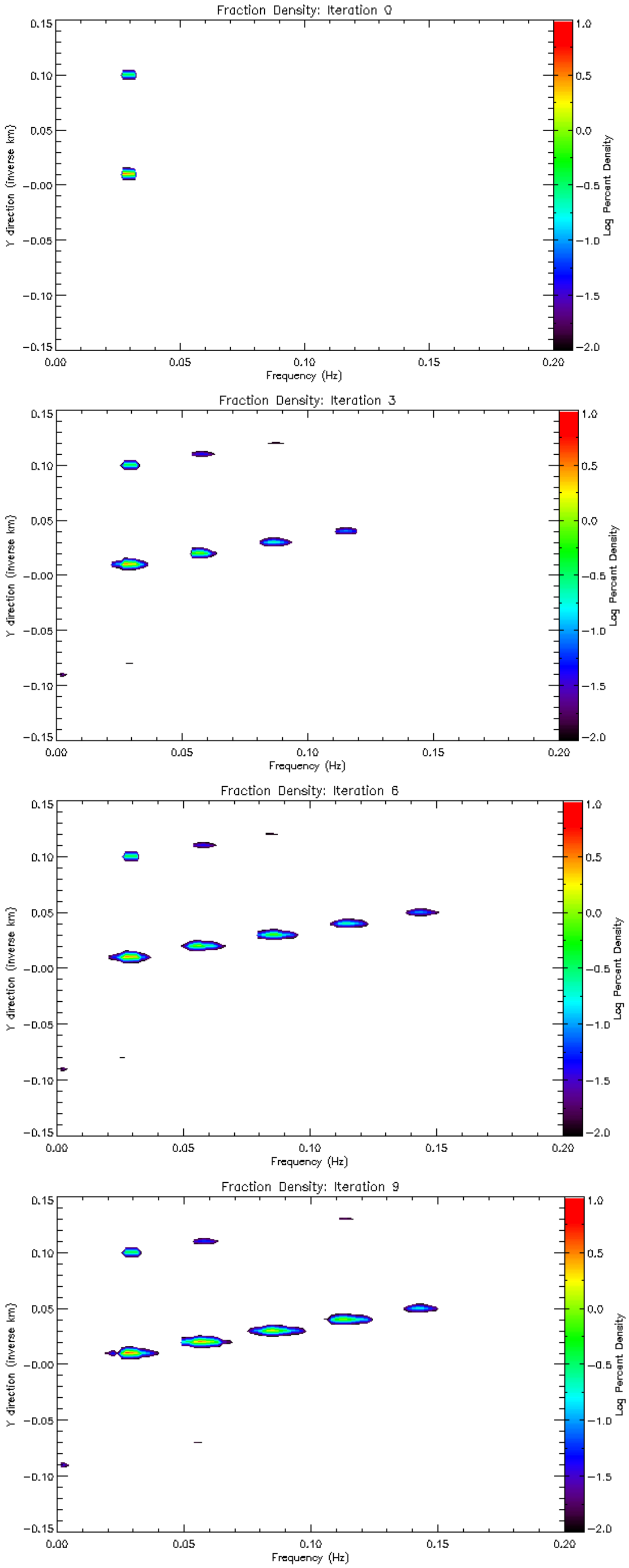

Figure 1: Four plots of the non-linear mesoscale modal prediction model, for a two-stream instability case. The background ionospheric state, and initial perturbations put to the system are described in the text above. The fractional density variation amplitude for each Fourier mode is represented by colored intensity. The horizontal axis is frequency and the vertical axis is inverse kilometers for the eastward direction. The top plot is the initial set of modes. Plots 2-4 show the evolution of the modal structure with iteration.

IMPACT/APPLICATIONS

MAPS is a data assimilative system operating on spatial scales from a few hundred kilometers to a few meters. As such it can be applied to DoD regional theatres where data availability may be difficult to acquire due to the hostile environment. MAPS can take large-scale data observations, combined with whatever data can be obtained to constrain the result, and can make specifications and predictions of the RF environment over the region of interest.

Similarly, on smaller scales MAPS can be used to specify and predict the irregularity environment in three spatial dimensions and as a function of time. This can be of use to GPS and other RF users who suffer interruptions to their applications due to strong scintillations – particularly in the equatorial sector.

Finally, MAPS can be used to investigate the physical drivers that cause ionospheric irregularities, and therefore advance our understanding of near Earth space physics, Space Weather, and the impact of Space Weather on human systems.

RELATED PROJECTS

Under a NASA rocket grant the PI will investigate medium-scale traveling ionospheric disturbances (TIDS) and their relations to the development of mid-latitude Spread-F.

Recently the PI has entered into a collaborative relationship with scientists from Los Alamos National Laboratory. One of the projects undertaken is the development of a diffraction tomography algorithm for scintillation TEC data obtained from GPS or other related observations.

The PI is involved with the Radio Astronomy Long Wavelength Array in New Mexico, and in the investigation of small scale ionospheric structures ~ 1 km spatial scale that will be observed with the array.

PUBLICATIONS

As the model has just completed testing, two initial archival papers describing the technique, and validation of the technique are in preparation, but have not yet been submitted.